

# How to measure the parity of the $\Theta^+$ in $\vec{p}\vec{p}$ collisions

C. Hanhart<sup>1</sup>, M. Büscher<sup>1</sup>, W. Eyrich<sup>2</sup>, K. Kilian<sup>1</sup>, U.-G. Meißner<sup>1,3</sup>,  
F. Rathmann<sup>1</sup>, A. Sibirtsev<sup>1</sup>, and H. Ströher<sup>1</sup>

<sup>1</sup>Institut für Kernphysik, Forschungszentrum Jülich GmbH,  
D–52425 Jülich, Germany

<sup>2</sup>Physikalisches Institut, Universität Erlangen,  
Erwin-Rommel-Str. 1, D–91058 Erlangen, Germany

<sup>3</sup>Helmholtz-Institut für Strahlen- und Kernphysik (Theorie), Universität Bonn  
Nußallee 14-16, D–53115 Bonn, Germany

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## Abstract

Triggered by a recent paper by Thomas, Hicks and Hosaka, we investigate which observables can be used to determine the parity of the  $\Theta^+$  from the reaction  $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$  near its production threshold. In particular, we show that the sign of the spin correlation coefficient  $A_{xx}$  for small excess energies yields the negative of the parity of the  $\Theta^+$ . The argument relies solely on the Pauli principle and parity conservation and is therefore model-independent.

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1. There is increasing experimental evidence for an exotic baryon with strangeness  $S = +1$ , the  $\Theta^+(1540)$ , see e.g. [1,2,3,4,5], preceded and complemented by a flurry of theoretical activity, see e.g. [6,7,8,9,10]. Experimental activities are now trying to pin down the quantum numbers of the  $\Theta^+$ ; in particular the parity  $\pi(\Theta^+)$  of this state is so far not determined experimentally, and the theoretical predictions allow for both possibilities. For example the chiral soliton model points at a positive parity state [7,8] whereas lattice calculations indicate a negative parity state for the pentaquark ground state [10], just to name a few. It is thus of utmost importance to determine  $\pi(\Theta^+)$  to further constrain the internal dynamics and structure of this exotic state.

The determination of the internal parity of a state is in general difficult, for any signal gets distorted by the interference of the resonance amplitude with the background [11]. Thus, in order to unambiguously pin down the parity of

a state from an angular distribution, one needs to know the background rather precisely. This makes it difficult to get model-independent results. A way to minimize the impact of the background would be to also measure the polarization of the decay products of the resonance as proposed in Ref. [12], however, these are extremely difficult measurements. In a recent work, Thomas, Hicks and Hosaka have proposed an alternative method to unambiguously determine the parity of the  $\Theta^+$  by looking at  $\vec{p}\vec{p} \rightarrow \Theta^+\Sigma^+$  close to the production threshold [13]. The idea relies only on the conservation of total angular momentum and parity in strong interactions and is therefore completely independent of the reaction mechanism. The same method was proposed by Pak and Rekalo to determine the parity of the kaon [14].

In this paper we will discuss this proposal in more detail. To be specific we will supply first a discussion of the most relevant observable including its angular structure and energy dependence in the near threshold regime, and second a brief discussion of its experimental boundary conditions as well as its feasibility. Let us start, however, with a repetition of the argument by Thomas et al. It is well known that the Pauli principle closely links spin and parity of a two nucleon state, since the relation  $(-)^{S+L+T} = -1$  holds, where  $T$  denotes the total isospin of the two nucleon system (for  $pp$   $T = 1$ ),  $L$  the angular momentum and  $S$  the total spin. Thus, a spin triplet (singlet)  $pp$  pair has to be in an odd (even) parity state. As a consequence, selecting the spin of a  $pp$  state implies preparing its parity. From the argument given it also follows that the corresponding reaction from a  $pn$  initial state does not allow to prepare the initial parity, for a  $pn$  state is an admixture of  $T = 1$  and  $T = 0$  states.

Close to the production threshold only  $s$ -waves are kinematically allowed in the final state. Consequently, a negative parity  $\Theta^+$  can only originate from a spin triplet initial  $pp$  state while a positive parity  $\Theta^+$  can only stem from a spin singlet  $pp$  state. In Refs. [15,16,17] it was shown, that a measurement of the spin correlation parameters  $A_{xx}$ ,  $A_{yy}$ ,  $A_{zz}$  as well as the unpolarized cross section allows to project on the individual initial spin states. More precisely

$$\begin{aligned} {}^1\sigma_0 &= \sigma_0(1 - A_{xx} - A_{yy} - A_{zz}) , \\ {}^3\sigma_0 &= \sigma_0(1 + A_{xx} + A_{yy} - A_{zz}) , \\ {}^3\sigma_1 &= \sigma_0(1 + A_{zz}) , \end{aligned} \tag{1}$$

where the spin cross sections are labeled following the convention of Ref. [15] as  ${}^{2S+1}\sigma_{M_S}$ , with  $S$  the total spin of the initial state and  $M_S$  its projection;  $\sigma_0$  denotes the unpolarized cross section. Therefore, if only  $\Sigma^+\Theta^+$   $s$ -waves contribute and the  $\Theta^+$  has positive parity, only  ${}^1\sigma_0$  would be non-vanishing.

Unfortunately, longitudinal polarization (needed for  $A_{zz}$ ) is not easy to prepare. However, the following linear combination projects on spin triplet initial

states and no longitudinal polarization is needed:

$${}^3\sigma_\Sigma = \frac{1}{2}({}^3\sigma_0 + {}^3\sigma_1) = \frac{1}{2}\sigma_0(2 + A_{xx} + A_{yy}) . \quad (2)$$

Thus, if the  $\Theta^+$  has positive parity, then  $(A_{xx} + A_{yy})$  must go to a value of  $-2$  as the energy approaches the threshold. Since  $A_{xx}$  and  $A_{yy}$  individually have to go to  $-1$ , in the following sections we will concentrate on a study of  $A_{xx}$  only.

In the next section we will investigate the general structure of the amplitude that will allow us to move away from the threshold region. To be specific, we will discuss in some detail the result one should get for  $A_{xx}$  in the reaction  $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$  under the assumption that the  $\Theta^+$  has spin  $1/2$ . Note that, if its spin were  $3/2$ ,  ${}^3\sigma_\Sigma$  would still be non-zero close to threshold only if the parity were negative. However, the spin formalism would be more complicated. Given the strong theoretical arguments in favor of a spin- $1/2$  pentaquark we do not consider this option in detail. In addition, we take the  $\Theta^+$  as being a stable state, for the narrow width of the  $\Theta^+$  will not change any of the arguments given.

**2.** In this section we closely follow Ref. [17]. (For a discussion of the threshold region also see Ref. [18].) For the general structure of the matrix element for  $pp \rightarrow \Sigma^+\Theta^+$  we may write

$$M = H(I I') + i\vec{Q} \cdot (\vec{S} I') + i\vec{A} \cdot (\vec{S}' I) + (S_i S_j') B_{ij} , \quad (3)$$

where  $I = (\chi_2^T \sigma_y \chi_1)$ ,  $I' = (\chi_4^\dagger \sigma_y (\chi_3^T)^\dagger)$ ,  $\vec{S} = \chi_1^T \sigma_y \vec{\sigma} \chi_2$  and  $\vec{S}' = \chi_3^\dagger \vec{\sigma} \sigma_y (\chi_4^\dagger)^T$ . Here  $\chi_i$  denotes the Pauli spinors for the incoming nucleons (1,2) and outgoing baryons (3,4) and  $\vec{\sigma}$  denotes the usual Pauli spin matrices. We focus on the close to threshold regime and restrict ourselves to a non-relativistic treatment of the outgoing particles. This largely simplifies the formalism since a common quantization axis can be used for the complete system. The amplitudes  $H$  and  $\vec{A}$  correspond to a spin singlet initial  $pp$  state;  $\vec{Q}$  and  $B_{ij}$  correspond to a spin triplet initial  $pp$  state.

The whole system is characterized by the initial (final) cms momentum vector  $\vec{p}$  ( $\vec{p}'$ ) as well as the axial vectors  $\vec{S}$  and  $\vec{S}'$ . In order to construct the most general transition amplitude that satisfies parity conservation, we combine the vectors and axial vectors given above such that the final expressions form a scalar (pseudoscalar) for reactions where the final state has positive (negative) intrinsic parity. As described in the introduction, the Pauli principle requires  $H$  and  $\vec{A}$  ( $\vec{Q}$  and  $B_{ij}$ ) to be even (odd) in  $\vec{p}$ . These two conditions together strongly constrain the number of allowed structures for the various amplitudes. To make the notation transparent we will use the parity of the

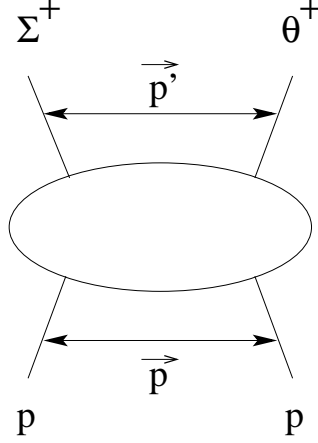


Fig. 1. Illustration of the reaction.

$\Theta^+$  as a superscript to the amplitudes. Keeping only terms which are at most quadratic in  $\vec{p}'$  we write for a positive parity  $\Theta^+$

$$\begin{aligned}
H^+ &= h_0^+ , \\
\vec{A}^+ &= \frac{a_0^+}{\Lambda^2} (\hat{p} \times \vec{p}') (\hat{p} \cdot \vec{p}') , \\
\vec{Q}^+ &= \frac{q_0^+}{\Lambda} (\hat{p} \times \vec{p}') , \\
B_{ij}^+ &= \frac{1}{\Lambda} \left( b_0^+ \delta_{ij} (\hat{p} \cdot \vec{p}') + b_1^+ p_i p_j' + b_2^+ p_j p_i' + b_3^+ p_i p_j (\hat{p} \cdot \vec{p}') \right) , \quad (4)
\end{aligned}$$

and in case of a negative parity  $\Theta^+$

$$\begin{aligned}
H^- &= 0 , \\
\vec{A}^- &= \frac{1}{\Lambda} \left( a_0^- \vec{p}' + a_1^- \hat{p} (\hat{p} \cdot \vec{p}') \right) , \\
\vec{Q}^- &= q_0^- \hat{p} + \frac{q_1^-}{\Lambda^2} \vec{p}' (\hat{p} \cdot \vec{p}') , \\
B_{ij}^- &= \epsilon^{ijk} \left( b_0^- \hat{p}_k + \frac{b_1^-}{\Lambda^2} \vec{p}_k' (\hat{p} \cdot \vec{p}') \right) + \frac{1}{\Lambda^2} (\hat{p} \times \vec{p}')_j (b_2^- \vec{p}_i' + b_3^- \hat{p}_i (\hat{p} \cdot \vec{p}')) , \quad (5)
\end{aligned}$$

where  $\hat{p} = \vec{p}/|\vec{p}|$  and the scale  $\Lambda$  was introduced to make the dimensions of the coefficients equal. Below we estimate the size of  $\Lambda$  on dimensional grounds. Then one expects all amplitudes to be of the same order of magnitude. The coefficients are functions of  $p^2$ ,  $p'^2$  and  $(\vec{p} \cdot \vec{p}')^2$ . To eliminate linearly dependent structures the reduction formula given in Appendix B of Ref. [17] may be used.

In the near threshold regime the only amplitudes that contribute for a neg-

ative parity  $\Theta^+$  are  $q_0^-$  and  $b_0^-$ , corresponding to the transition  ${}^3P_0 \rightarrow {}^1S_0$  and  ${}^3P_1 \rightarrow {}^3S_1$ , respectively. Analogously, for a positive parity  $\Theta^+$  the only contributing amplitude is  $h_0^+$ , corresponding to  ${}^1S_0 \rightarrow {}^1S_0$ .

For our discussion we express  $A_{xx}$  in terms of the amplitudes given above:

$$4\sigma_0 = |H|^2 + |\vec{Q}|^2 + |\vec{A}|^2 + |B_{mn}|^2, \quad (6)$$

$$4A_{xx}\sigma_0 = -|H|^2 - 2|Q_x|^2 + |\vec{Q}|^2 - |\vec{A}|^2 - 2|B_{xm}|^2 + |B_{nm}|^2. \quad (7)$$

where summation over  $m$  and  $n$  is assumed. Keeping only terms up to and including  $p'^2$  we obtain for a positive parity  $\Theta^+$

$$A_{xx} = -1 + \alpha \frac{p'^2}{\Lambda^2} + O\left(\frac{p'^4}{\Lambda^2}\right) \quad (8)$$

where

$$\begin{aligned} \alpha = \frac{2}{|h_0^+|^2} & \left( |q_0^+|^2 \sin^2(\theta) \cos^2(\phi) + |a_0^+|^2 \sin^2(\theta) \cos^2(\theta) + \right. \\ & (|b_1^+|^2 + |b_2^+|^2 \sin^2(\phi)) \sin^2(\theta) + \\ & \left. (|b_0^+|^2 + |b_0^+ + b_1^+ + b_2^+ + b_3^+|^2) \cos^2(\theta) \right). \end{aligned} \quad (9)$$

This expression reproduces the threshold behavior of  $A_{xx}$  (approaching  $-1$ ) as discussed in the first section. Exactly at threshold the cross section vanishes, however, Eq. (9) allows one to estimate the energy dependence of  $A_{xx}$  based on rather general arguments.

In case of a negative parity  $\Theta^+$  we have

$$A_{xx} = \frac{|q_0^-|^2}{|q_0^-|^2 + 2|b_0^-|^2} \left( 1 - \beta \frac{p'^2}{\Lambda^2} + O\left(\frac{p'^4}{\Lambda^2}\right) \right) \quad (10)$$

where

$$\begin{aligned}
\beta = & \frac{1}{|q_0^-|^2} \left( -2\text{Re}(q_0^- * q_1^-) \cos^2(\theta) + (|a_0^-|^2 \sin^2(\theta) + |a_0^- + a_1^-|^2 \cos^2(\theta)) \right. \\
& \left. + 2\text{Re}(b_0^- * b_2^-) \sin^2(\theta)(\cos^2(\phi) - \sin^2(\phi)) \right) \\
& + \frac{1}{|q_0^-|^2 + 2|b_0^-|^2} \left( 2\text{Re}(q_0^- * q_1^- + 2b_0^- * b_1^-) \cos^2(\theta) \right. \\
& \left. + (|a_0^-|^2 \sin^2(\theta) + |a_0^- + a_1^-|^2 \cos^2(\theta)) + \right. \\
& \left. + 2\text{Re}(b_0^- * b_2^-) \sin^2(\theta) \right) . \tag{11}
\end{aligned}$$

This formula only holds for non-vanishing values of  $q_0^-$ . (If  $q_0^-$  would vanish, the denominator in the third row of this expression needs to be replaced by  $1/|q_0^-|^2$ .)

Because of the presence of two amplitudes even at threshold the asymptotic value of  $A_{xx}$  is not equal to +1. In this case  $A_{xx}$  measures the ratio of the two amplitudes.

Let us briefly discuss the angular dependence of  $A_{xx}$ . We observe that for both scenarios there is no preferred angular range. Thus one can perform the experiment angular integrated or only for special kinematics of the  $\Sigma^+\Theta^+$  final state. The information content will be the same. Secondly, one might ask whether it is sufficient to measure  $A_{xx}$  at some single low excess energy and then verify that only  $s$ -waves contribute by analysing the angular distribution. The above formulas show that this will not work. If only the  $p$ -wave amplitudes  $b_1^+$  ( $a_0^-$ ) contribute considerably in case of a positive (negative) parity pentaquark, the differential cross section would still be isotropic. It is therefore necessary to study the energy dependence of  $A_{xx}$ , as was also stressed in Ref. [13].

**3.** The next step is to estimate the energy range where the formulas given in the previous section should give sensible results.

The reaction  $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$  near threshold is characterized by a large momentum transfer  $t \sim -m_x M_N$ , where  $m_x$  denotes the mass produced  $m_x = M_\Sigma + M_\Theta - 2M_p$  and  $M_N$  ( $M_\Sigma$ ) denotes the nucleon ( $\Sigma$ ) mass. Since in a non-relativistic picture  $t$  is a measure of the size of the interaction region, it sets the scale for the onset of higher partial waves. Thus, we can identify  $\Lambda^2$  with  $-t$ . We express  $p'$  in terms of  $Q$ , the excess energy above the  $\Sigma^+\Theta^+$  threshold,  $Q = p'^2/(2\mu)$ , where  $\mu$  denotes the reduced mass of the  $\Sigma^+\Theta^+$  system, and find that

$$\frac{p'^2}{\Lambda^2} \sim 2 \frac{Q}{M_N}$$

For our estimates of the energy dependence of the polarization observables we need  $(p'/\Lambda)^2 \ll 1$ . If we request  $(p'/\Lambda)^2 \sim 0.1$  we find that the expressions

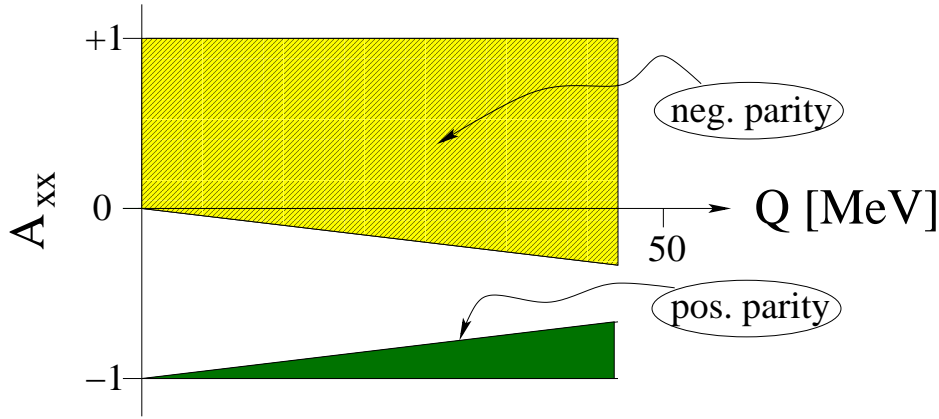


Fig. 2. Schematic presentation of the result for  $A_{xx}$  for the two possible parity states of the  $\Theta^+$ . For either option realized the corresponding data should fall into the area indicated. In case of a negative parity the threshold value depends on the ratio of the strength of the two possible  $s$ -wave amplitudes.

given above should be applicable for  $Q < 50$  MeV. The expected signal for  $A_{xx}$  is sketched in Fig. 2.

Implicitly we assumed that there is no strong  $\Theta^+\Sigma^+$  final state interaction that would introduce an additional large scale into the system. This is justified, because most of those meson exchanges that potentially could lead to a strong final-state interaction are either absent or should be weak: (i) a single pion exchange between  $\Theta^+$  and  $\Sigma^+$  is not possible due to the isoscalar nature of the pentaquark, (ii) a strong coupling of the  $\Theta^+$  to  $NK$  is excluded due to its small width and (iii) there can also be no strong coupling of the  $\Theta^+$  to the iso-scalar two pion exchange, known to be responsible for the medium range attraction of the  $NN$  interaction, since then the  $\Theta^+$  should not be seen equally narrow in nuclear reactions [2] and in elementary production reactions on a single nucleon [4,5].

**4.** We also want to briefly comment on the possible influence of the background on the signal. In principle there is the admittedly rather unlikely possibility that the pentaquark signal observed does—at least to some extent—stem from an interference of the  $\Theta^+$  production amplitude with the background. How would this change our analysis? To simplify this discussion we will assume that the observables are fully angular integrated. Thus, we do not have to worry about the interference amongst different partial waves. In addition, we will only discuss the observables in threshold kinematics.

The observable  ${}^3\sigma_\Sigma$  defined in Eq. (2) is a projector on spin triplet initial states irrespective of the final states. Thus, even if the observed signal would be due to an interference of a positive parity  $\Theta^+$  amplitude with the background,  $A_{xx}$  would approach  $-1$  as the energy approaches the  $\Theta^+$  production threshold.

The situation is a little more complicated for the negative parity  $\Theta^+$ , for here two amplitudes contribute at threshold. In this case the threshold amplitude

would read

$$A_{xx} = \frac{2\text{Re}(q_B^-^* q_R^-) + |q_R^-|^2}{2\text{Re}(q_B^-^* q_R^- + 2b_B^-^* b_R^-) + |q_R^-|^2 + 2|b_R^-|^2}, \quad (12)$$

where we introduced the following decomposition (analogously for  $b_0^-$ )  $q_0^- = q_B^- + q_R^-$ , where the first and second term denote the background and the resonance amplitude, respectively. In addition we assumed that all those terms that are at least linear in the resonance amplitude are (miss)interpreted as  $\Theta^+$  resonance signal. The sign of  $\text{Re}(q_B^-^* q_R^-)$  is not fixed. Thus, if the interference term dominates over the pure resonance contribution, the value of  $A_{xx}$  can be negative even if the pentaquark has negative parity. However, the denominator of  $A_{xx}$  in Eq. (12) denotes the differential cross section and is thus bound to be positive (otherwise, already the unpolarized measurement would tell that the signal is dominated by an interference) and consequently the term  $(2\text{Re}(b_B^-^* b_R^-) + |b_R^-|^2)$  must be positive. In this case it is straightforward to show that the depolarization coefficient  $D_{zz}$  as well as the spin correlation coefficient  $A_{zz}$  both take unphysical values larger than 1. On the other hand one finds for these observables in case of a positive parity  $\Theta^+$  the asymptotic values 0 and -1 for  $D_{zz}$  and  $A_{zz}$ , respectively.

Thus, a simultaneous investigation of  $A_{xx}$  and either  $D_{zz}$  or  $A_{zz}$  allows to unambiguously determine the parity of the  $\Theta^+$  even for the unlikely situation that an interference term is missinterpreted as a resonance signal.

A similar discussion for the possible influence of background amplitudes on the interpretation of polarization observables in terms of the  $\Theta^+$  parity for other reactions is urgently called for. Within particular models this was done in Refs. [12,11].

**5.** We would like to make some comments about the possible experimental realization. Double polarization experiments with polarized proton beams with momenta up to 3.7 GeV/c and polarized internal or external targets can be carried out at the COoler SYnchrotron COSY-Jülich. Two experimental facilities, the magnetic spectrometer ANKE and the time-of-flight spectrometer TOF, can be used for such measurements. Since both cannot detect photons the relevant reaction channels are:

$$\Theta^+ \Sigma^+ \rightarrow \Sigma^+ [pK^0] \rightarrow \begin{pmatrix} p\pi^0 \\ n\pi^+ \end{pmatrix} [p(\pi^+\pi^-)] .$$

This implies  $K^0$  identification by the invariant mass and the  $\Sigma^+$  by missing mass and asking for an additional proton ( $\Sigma^+ \rightarrow p\pi^0$ ) or an additional positive pion ( $\Sigma^+ \rightarrow n\pi^+$ ). For the candidate events  $\{\Sigma^+, K^0\}$  the invariant mass of the  $[pK^0]$  subsystem has to be reconstructed.

The  $\Theta^+$  production cross section from the reaction  $pp \rightarrow \Sigma^+ \Theta^+$  has been esti-



mated within a meson exchange model calculation [19] taking the  $\Theta^+$  width of 5 MeV. Its value at  $Q \leq 100$  MeV above the  $\Sigma^+\Theta^+$  threshold is about 80-120 nb, which is about a factor of 20 smaller than the most recent estimation [20] using a  $\Theta^+$  width of 20 MeV. At TOF a  $5\sigma$  signal in the  $K^0p$  invariant mass distribution has been observed in the reaction  $pp \rightarrow \Sigma^+ K^0 p$  at a beam momentum of 2.95 GeV/c, corresponding to an excess energy well below 50 MeV. The very preliminary cross section estimate is of the order of a few hundred nb. The width of the peak is about 25 MeV, corresponding to the experimental resolution of TOF. At ANKE a proposal has been accepted to measure the reaction  $pp \rightarrow K^0 p \Sigma^+$  [21]. These measurements will be carried out in spring 2004.

For the envisaged future double polarization experiments at COSY a frozen spin  $\text{NH}_3$  target (TOF) [22] and a polarized internal hydrogen gas target utilizing a storage cell (ANKE) [23] are presently being developed.

**6.** To summarize, we have extended the argument of Ref. [13] and specified how the parity of the  $\Theta^+$  can be determined in the reaction  $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$ . In particular, we have identified an ideally suited observable, namely the spin correlation coefficient  $A_{xx}$ , whose sign agrees with  $\pi(\Theta^+)$  near threshold. We have further discussed the information content of the angular distribution of  $A_{xx}$ , and identified the relevant energy range for the measurement. If the final-state interaction between the  $\Sigma^+$  and the  $\Theta^+$  is weak, as can be assumed given the known or anticipated properties of the  $\Theta^+$ , the above mentioned identification of the parity with the sign of  $A_{xx}$  holds for an excess energy (with respect to the  $\Sigma^+\Theta^+$  threshold) below 50 MeV. Finally, we have briefly discussed the experimental feasibility of this proposal and shown that such a determination of the  $\Theta^+$  parity  $\pi(\Theta^+)$  is indeed possible at COSY.

**Note added:** After the original submission of this letter a model calculation for  $A_{xx}$  for the reaction  $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$  appeared [24]. The results of this phenomenological approach lie well within the range given in Fig. 2.

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